ABSTRACT

Virtually all of the fatigue crack propagation data reported in the literature for structural alloys are generated under simple zero-tension cycling. The direct application of this data to problems involving large welded structures subjected to operating stress cycles a p p r o a c h i n g fully-reversed tension-compression is questionable. The present study shows that the compression portion of fully-reversed tension-compression cycling can contribute substantially to fatigue crack growth rates in plate-thickness, medium-to-high-strength alloys. Data from several alloys show a 50 percent increase in fatigue crack growth rates due to tension-compression cycling. The implications of these findings and methods for applying the results of this study are discussed.

PROBLEM STATUS

This report completes one phase of the problem; work on other aspects of the problem is continuing.

AUTHORIZATION

BLANK PAGE

EFFECT OF TENSION-COMPRESSION CYCLING ON FATIGUE
CRACK GROWTH IN HIGH-STRENGTH ALLOYS

INTRODUCTION

Crack growth by low-cycle fatigue is a potential failure mechanism for large welded structures. Most fatigue crack propagation data reported in the literature are generated under zero-tension cycling. However, critical regions in cyclically-loaded structures frequently undergo more complex loading than simple zero-tension because of service loads and residual stresses from fabrication and/or shakedown. Therefore, it is of considerable practical interest to study the relationships between data obtained from simple laboratory tests and more complex loading which can be anticipated in actual structural service.

One of the most common aspects of complex loading which has occasionally been recognized, but which has not received adequate attention, is the contribution that the compression portion of tension-compression cycling can make to fatigue crack growth. Illg and McEvily (1) obtained fatigue crack propagation data on 2024-T3 aluminum alloy sheet and reported that crack growth rates were only slightly faster under fully-reversed tension-compression cycling. Donaldson and Anderson (2) made a comparison among Illg and McEvily's data and other zero-tension (or slightly offset tension-tension) data on 2024-T3 aluminum from several sources and concluded that the results for the two types of loading were not greatly different. Hudson and Scardina (3) studied fatigue crack growth in 7075-T6 aluminum alloy sheet under both types of loading and concluded that the compression portion of the loading cycle did not significantly affect crack growth in their tests.

Based upon these results obtained from sheet aluminum alloys, it was generally concluded that the compression portion of tension-compression cycling could safely be ignored in all design situations (4,5). However, it has been noted in low-cycle fatigue tests on a plate-thickness high-strength steel (6) that notched specimens failed significantly earlier in crack propagation under fully-reversed tension-compression cycling than under zero-tension cycling at the same load amplitude. Gurney (7) has made similar observations on ferrous alloys, and he has proposed an equivalent stress concept to account for the accelerating effects of tension-compression cycling on fatigue crack growth.

With this background in mind, it was decided to determine if the compression portion of tension-compression cycling does contribute substantially to crack growth in several high-strength alloys, and if so, to determine the magnitude of these effects so that researchers and designers relying upon zero-tension data reported in the literature could reasonably estimate how these data would apply to fully-reversed tension-compression cycling.

EXPERIMENTAL DETAILS

Axial-loaded plate specimens containing embedded surface cracks were cycled under (a) constant-load-amplitude zero-tension and (b) fully-reversed tension-compression cycling.

The materials studied included 9Ni-4Co-0.20C and HY-80 quenched-and-tempered steels and Ti-6Al-4V alloy. All test materials were received as 1-in.-thick rolled plate stock. The tensile properties of the test materials are shown below.

Tensile Properties of Test Materials

Material	0.2% Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Reduction of Area (%)	Elongation (%)
9Ni-4Co-0.20C steel	183	201	66.0	17.8
HY-80 steel	109	127	68.9	20.5
Ti-6Al-4V	123	135	25.0	10.0

The materials were tested as axial-loaded surface-cracked plate specimens (Fig. 1). An Elox surface notch of semicircular shape (i.e., a depth-to-length ratio of 0.50) was used as the crack starter. Macrofeatures of the fatigue surfaces indicated that crack front profiles remained semicircular throughout the duration of their growth. Therefore, the assumption was carried forth that a uniform stress-intensity distribution existed around the periphery of the crack front. The equation (Ref. 8) used to calculate crack tip stress-intensity factors is

$$K = \sqrt{1.21\pi\sigma^2 a/Q}$$

where K is the stress-intensity factor, σ is the nominal gross section stress, a is the crack depth, and Q is a flaw shape parameter. Maximum nominal stress levels encountered in fatigue cycling varied between 50 and 60 percent of yield strength stress. Crack length observations were made on the surface of the specimens using an optical micrometer. The crack depth a was assumed to be equal to half the total surface crack length 2c.

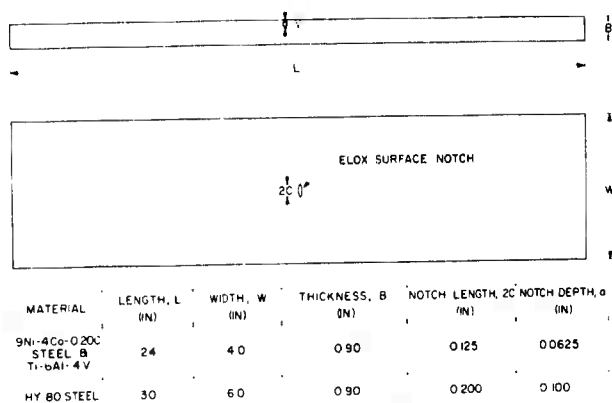| MATERIAL	LENGTH, L (IN)	WIDTH, W (IN)	THICKNESS, B (IN)	NOTCH LENGTH, 2C (IN)	NOTCH DEPTH, a (IN)
9Ni-4Co-0.20C STEEL & Ti-6Al-4V	24	4 0	0 90	0 125	0.0625
HY 80 STEEL	30	6 0	0 90	0 200	0 100

Fig. 1 - Dimensions and configuration of the test specimens and crack-starter notch

Specimens were cycled under (a) constant load amplitude zero-tension and (b) fully-reversed tension-compression cycling (Fig. 2). These loading cycles correspond to load ratios R (where R = minimum load/maximum load) of zero and -1.0, respectively. In each case, companion specimens of a test material were cycled to failure at a constant-load amplitude with R = 0 and R = -1.0. All stress-intensity factor values reported were calculated using only the tension portion of the loading cycle.
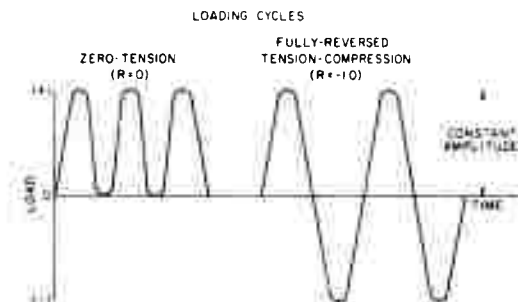
Fig. 2 - Schematic of the two loading cycles
used in the tests

RESULTS

The results of this study are given in Figs. 3 and 4. In every instance, specimens which were tension-compression cycled failed significantly sooner than companion specimens cycled at zero-tension. Both crack initiation from the crack-starter notch and crack propagation were accelerated under tension-compression cycling. Typical examples of the differences in crack propagation life between zero-tension and tension-compression cycling are shown in Fig. 3. Companion specimens of each test material were cycled to maximum nominal stresses of 50 to 60 percent of the yield strength stress. These plots show that crack propagation occurred more rapidly at all stages of crack growth under tension-compression cycling. These plots also show that in high-strength alloys, such as 9Ni-4Co-0.20C steel and Ti-6Al-4V, fatigue failures in the low-cycle life region (i.e., less than 100,000 cycles) can occur at cyclic stress levels well below yielding. In fact, in all of the 0.90-in.-thick plate specimens tested, including HY-80, it was possible to obtain through-thickness flaws from small starting notches in well under 100,000 cycles.

Log-log plots of fatigue crack growth rates dc/dN as a function of the tension stress-intensity factor range ΔK for all three materials studied are shown in Fig. 4. In each case the data for the two loading cycles fall along separate curves, with the tension-compression cycling exhibiting faster crack growth rates over the entire range of ΔK values examined. Tension-compression cycling accelerated crack growth rates by approximately 50 percent in each material.
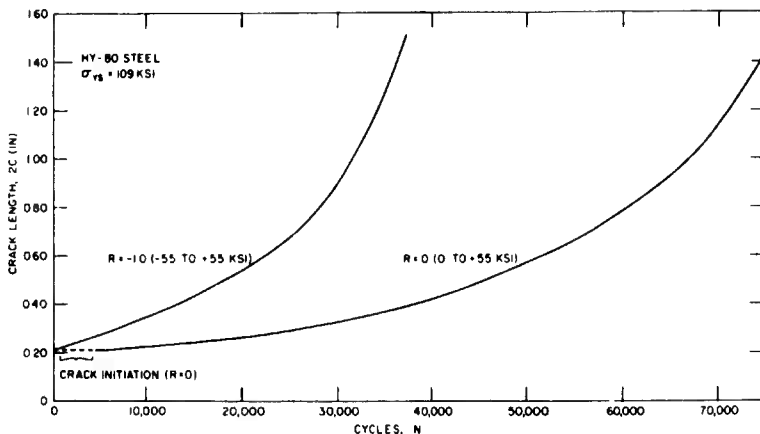
DISCUSSION

There are two viewpoints on fatigue crack propagation which can offer an explanation as to why nominal compressive loading can contribute to crack growth rates. Both
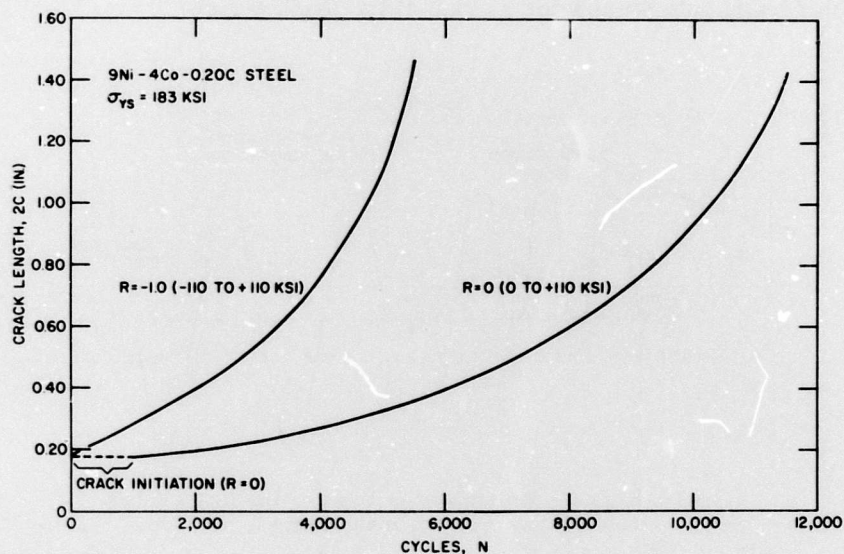
(a) plate specimens of 9Ni-4Co-0.20C steel subjected to zero-
tension (R = 0) and tension-compression (R = -1.0) cycling
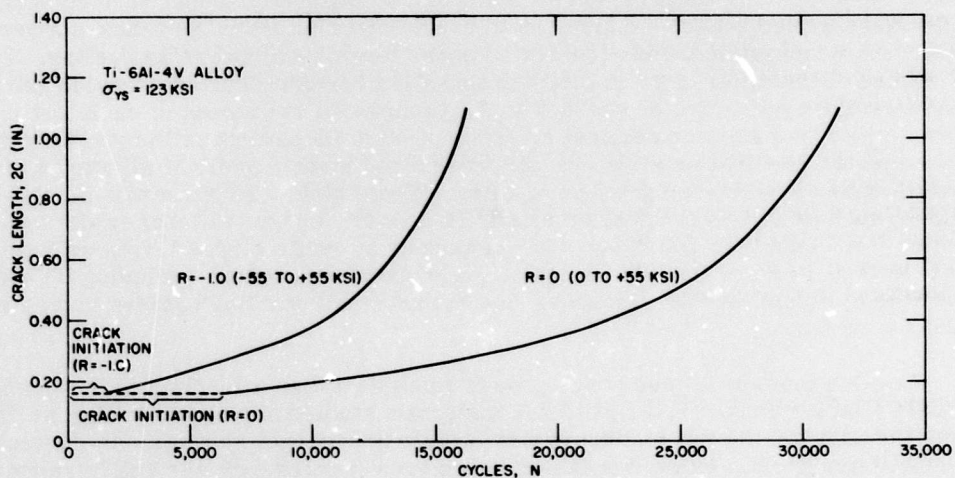
(b) Ti-6Al-4V plate specimens under constant-amplitude cycling
with R = 0 and R = -1.0

(c) HY-80 steel plate specimens under constant-amplitude cycling
with R = 0 and R = -1.0

Fig. 3 - Total surface crack length 2c vs cycles of repeated load N

viewpoints recognize that fatigue crack propagation results from plastically deformed
material residing at the tip of a sharp crack. Lehr and Liu (9) have proposed that fatigue
crack propagation is the result of cumulative damage caused by plastic strain cycling of
the material at the crack tip. The compression portion of tension-compression cycling
contributes to crack tip deformation and, therefore, to crack growth rates. Hubbard (10)
has observed fatigue crack growth under purely compressive cyclic loading. He postulated
that cracks do not propagate under totally compressive stresses, and sought to define
residual tensile stresses at crack tips under nominally compressive cycling. Although
his work is not directly applicable to tension-compression cycling, it points out that
crack tip stress fields do not necessarily follow in phase with nominal stresses under
cyclic loading.

It is well recognized that service loads and residual stresses resulting from fabrica-
tion and/or shakedown can result in structural materials experiencing cycling which
approaches fully-reversed tension-compression under loading from internal pressure.
Since virtually all of the fatigue crack propagation data appearing in the literature are
obtained under zero-tension cycling, the application of this data to structural design
situations is not evident. The mathematical form of these data generally is

$$da/dN = C \cdot K^m$$

where da/dN (or dc/dN) is the crack growth rate, K is the stress-intensity factor range
for zero-tension or tension-tension cycling, m is the power law exponent, and C is a
material constant. To ignore the compression portion of the cycle would tend to over
estimate the fatigue life, as shown in the results of this study. To calculate K based on
the full range of loading would seriously underestimate fatigue life. Since m usually
varies from approximately 2 to 4 for most steels (11), this would overestimate crack
growth rates by factors of 4 to 16. Therefore, it is recommended that zero-tension crack
growth rate data be increased by a correction factor of 1.5 for application to low-cycle-
fatigue design situations involving tension-compression cycling. This procedure would
be analogous to the adjustment for tensile mean stress effects which is included in the
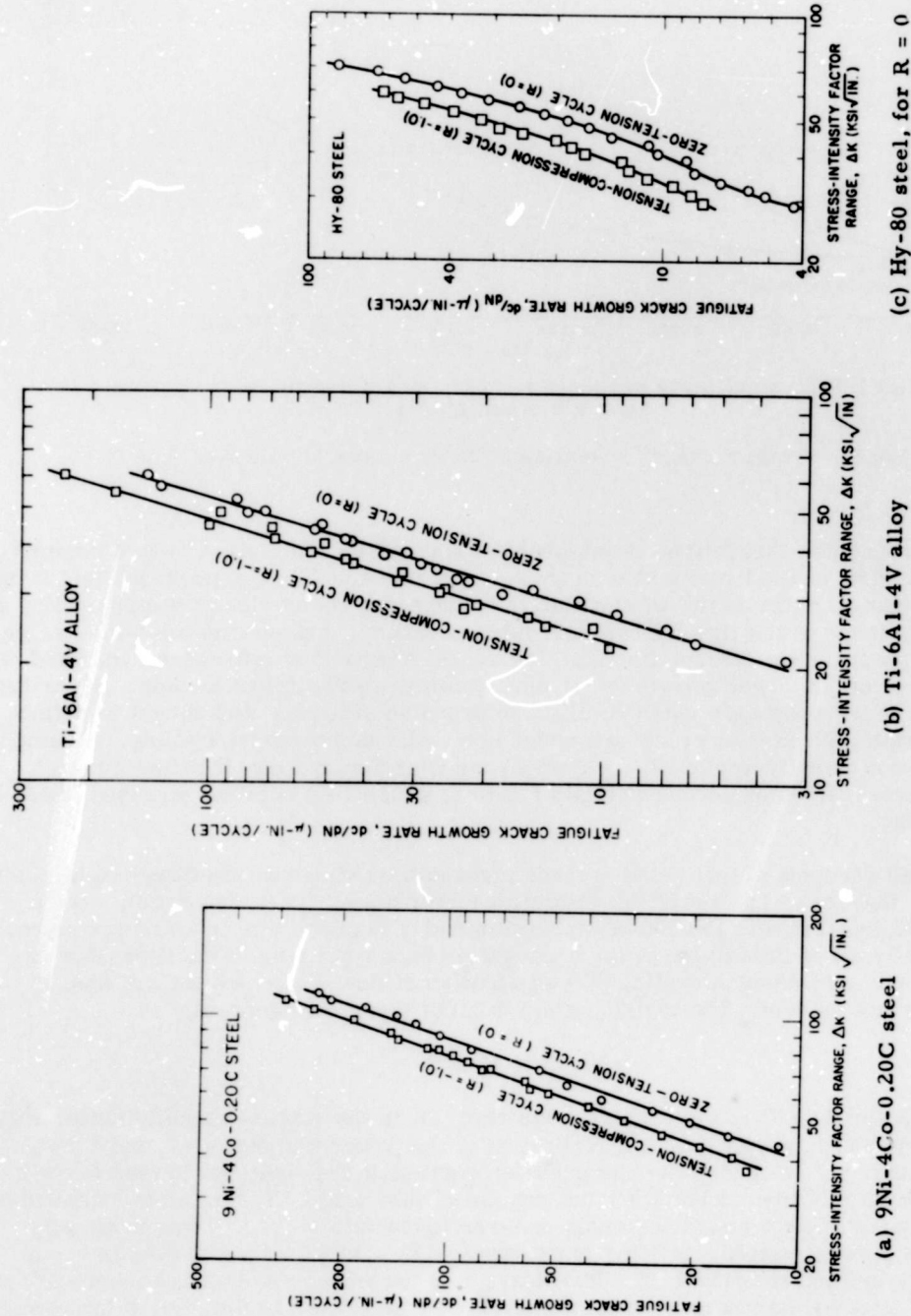analysis for cyclic operation of nuclear vessels (12).

T. W. CROOKER

Fig. 4 - Log-log plot of fatigue crack growth rate dc/dN as a function of the stress-intensity factor range ΔK. ΔK values were calculated using only the tension portion of the loading cycle

(a) 9Ni-4Co-0.20C steel

(b) Ti-6Al-4V alloy

(c) Hy-80 steel, for R = 0 and R = 1.0

SUMMARY AND CONCLUSIONS

Low-cycle-fatigue crack propagation tests were conducted on HY-80 and 9Ni-4Co-0.20C steels and on Ti-6Al-4V alloys under constant load amplitude zero-tension and fully-reversed tension-compression cycling. It was observed that the compression portion of fully-reversed tension-compression cycling contributed substantially to crack growth and resulted in an approximate 50-percent increase in crack growth rates, as compared with zero-tension cycling. It is concluded that this effect of tension-compression cycling in fatigue crack growth should be included in the design of structures against low-cycle-fatigue failure where compressive loading is a significant factor. Laboratory crack growth rate data generated under ordinary zero-tension loading should be corrected by a factor of 1.5 to account for the effects of fully reversed tension-compression cycling.

ACKNOWLEDGMENTS

REFERENCES

1. Illg, W., and McEvily, A.J., Jr., "The Rate of Fatigue-Crack Propagation for Two Aluminum Alloys Under Completely Reversed Loading," NASA Tech. Note D-52, Langley Research Center, Oct. 1959

2. Donaldson, D.R., and Anderson, W.E., "Crack Propagation Behaviour of Some Airframe Materials," in "Proceedings, Crack Propagation Symposium," Vol. 2, p. 375, Cranfield, England, Sept. 1961

3. Hudson, C.M., and Scardina, J.T., "Effect of Stress Ratio on Fatigue-Crack Growth in 7075-T6 Aluminum-Alloy Sheet," Eng. Fracture Mech., 1(No. 3):429 (April 1969)

4. Paris, P.C., "Fatigue Crack Growth," Third Annual Workshop in Fracture Mechanics, Denver, Colorado, August 7-19, 1966

5. Pelloux, R.M., "Crack Propagation Theories," Air Force Conference on Fatigue and Fracture of Aircraft Structures and Materials, Miami Beach, Florida, December 15-18, 1969.

6. Crooker, T.W., and Lange, E.A., "Fatigue Crack Propagation in a High-Strength Steel Under Constant Cyclic Load with Variable Mean Loads," NRL Report 6805, Nov. 1968

7. Gurney, T.R., "An Investigation of the Rate of Propagation of Fatigue Cracks in a Range of Steels," The Welding Institute Report E18/12/68, Dec. 1968

8. Tiffany, C.F., and Masters, J.N., "Applied Fracture Mechanics," in "Fracture Toughness Testing and Its Applications," ASTM STP 381, p. 249, Am. Soc. Testing Materials, Philadelphia, 1965

9. Lehr, K.R., and Liu, H.W., "Fatigue Crack Propagation and Strain Cycling Properties," Intern. J. Fracture Mech.," 5(No. 1):45 (March 1969)

10. Hubbard, R.P., "Crack Growth Under Cyclic Compression," Trans. ASME, J. Basic Eng., 91, Series D(No. 4):625 (Dec. 1969)

11. Crooker, T.W., and Lange, E.A., "The Influence of Yield Strength and Fracture Toughness of Fatigue Design Procedures for Pressure Vessel Steels," ASME Paper No. 70-PVP-19; also NRL Report 7036, Feb. 1970.

12. ASME Boiler and Pressure Vessel Code, Section III, Rules for Construction of Nuclear Vessels, 1965

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Naval Research Laboratory Washington, D.C. 20390	Unclassified
	2b. GROUP

3. REPORT TITLE

EFFECT OF TENSION-COMPRESSION CYCLING ON FATIGUE CRACK GROWTH
IN HIGH-STRENGTH ALLOYS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

This report completes one phase of a continuing problem.

5. AUTHOR(S) (First name, middle initial, last name)

T.W. Crooker

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 4, 1971	11	12

8a. CONTRACT OR GRANT NO	9a. ORIGINATOR'S REPORT NUMBER(S)
NRL Problem M01-25	
b. PROJECT NO	NRL Report 7220
RR 007-01-46-5432	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution
is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Dept. of the Navy (Office of Naval Research), Arlington, Va. 22217

13. ABSTRACT

Virtually all of the fatigue crack propagation data reported in the literature for structural alloys are generated under simple zero-tension cycling. The direct application of this data to problems involving large welded structures subjected to operating stress cycles approaching fully-reversed tension-compression is questionable. The present study shows that the compression portion of fully-reversed tension-compression cycling can contribute substantially to fatigue crack growth rates in plate-thickness, medium-to-high-strength alloys. Data from several alloys show a 50 percent increase in fatigue crack growth rates due to tension-compression cycling. The implications of these findings and methods for applying the results of this study are discussed.

DD FORM 1473 (PAGE 1)
1 NOV 65

9

S/N 0101-807-6801

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fatigue (materials)						
High strength steels						
Cyclic loads						
Crack propagation						
Titanium alloys						
Fracture mechanics						